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Energy and exergy analysis of typical renewable energy systems

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ABSTRACT

The use of renewable energy systems for real life applications has been increasing for the last few decades due to the growing concern about the global warming and environmental pollution. The renewable energy sources are clean and freely available in the nature, however, the efficient utilization is still a cause of concern among the scientific and business communities. This paper presents an extensive literature review on both the energy and exergy analyses of typical renewable energy systems including, solar thermal, solar photovoltaic and biomass cookstove. Some important conclusions from the literature survey has been drawn and summarized in this paper. Among all important aspects studied and summarized in this paper, it is found that most of the analysis carried out for renewable energy systems so far is based on the energy analysis. Also for all renewable energy systems, the performance based on exergy analysis, in general, is found to be lesser than that of the energy analysis.

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Nomenclature

A	area of the collector (m^2)
C_p	specific heat (J/kg-K)
C_{pw}	specific heat of water (kJ/kg-K)
c_1	calorific value of wood (kcal/kg)
c_2	calorific value of kerosene (kcal/kg)
C_{PAl}	specific heat of aluminium (J/kg K)
d	density of kerosene (g/cc)
E	energy (W)
Ex	exergy (W)
g	gravitational constant (m/s^2)
g_c	constant in Newtons Law
h	Plank constant
h_{ca}	heat transfer coefficient
h	specific enthalpy (kJ/kg)
H	enthalpy (kJ)
I_b	beam radiation (W/m^2)
I_d	direct radiation (W/m^2)
I_{sc}	short circuit current (Amps)
I_m	current corresponding to maximum power point (Amps)
I_s	intensity of solar radiation at any particular site (W/m^2)
M_1	initial mass of the cookstove with test fuel (kg)
M_2	mass of the cookstove, after burning the test for half an hour (kg)
m_{pot}	mass of pot (kg)
m	mass flow rate of air (Kg/s)
m_w	mass of water (kg)
m_{wd}	mass of wood (kg)
n_{ph}	number of photons falling on the surface of PV module
n	total number of vessels used
P_1	first pot
P_2	second pot
P_3	third pot
P_4	fourth pot
Q_c	energy incident on the collector (W)
Q_f	energy absorbed (W)
s	entropy (J/kg-K)
ΔT	temperature difference (K)
T	temperature (K)
u	specific internal energy (kJ/kg)
v	wind speed (m/s)
V_{oc}	open circuit voltage (V)
V_m	voltage corresponding to maximum power point (V)
w	mass of water in vessel (kg)
W	mass of vessel complete with lid and stirrer (kg)
x	volume of kerosene consumed (ml)
X	mass of fuel consumed (kg)
z	altitude coordinate (m)

Greek letters

α	absorptance of collector
ε	thermal exergy at temperature T
$\varepsilon(T_i)$	thermal exergy at temperature Ti
τ	transmittance of the collector
η	energy efficiency (%)
ψ	exergy efficiency (%)
η_{pce}	power conversion efficiency (%)

Subscripts

1	initial state
2	final state
a	ambient
Al	aluminium
cell	cell
chem	chemical
d	destroyed
elec	electrical
fp	final state of pot
fw	final state of water
htm	hytherm oil
in	input
ip	initial state of pot
iw	initial state of water
o	output
oc	open circuit
pce	power conversion efficiency
ph	photon
sc	short circuit
therm	thermal
wd	wood

1. Introduction

The present world energy scenario exhibits that most of the energy requirements are met from fossil fuels which cannot be newly formed at any significant rate therefore, the present stocks are finite. Also these fossil fuels are not environmental friendly and emits significant amount of pollutants causing serious environmental issues such as, global warming, ozone layer depletion and climate change. Renewable energy sources, with advantages of being environment friendly and abundant in availability are the promising option to meet the increasing demand of energy worldwide. However, the renewable energy systems suffer from low conversion efficiency therefore using the renewable energy systems for real life applications in regular practice requires special consideration. Performance of most of the renewable energy conversion systems is given based on energy analysis which is basically only the accounting of energies entering and exiting. Energy is based on the first law of thermodynamics and gives the quantity of energy only. While exergy is based on the second law of thermodynamics and represents the quality of energy and involves the irreversibility while analysing system efficiency. Exergy analysis identifies the causes, locations and magnitude of the system inefficiencies and provides the true measure how a system approaches to the ideal [1].

The main source of all the renewable and conventional energy sources is the sun, which is freely and abundantly available round the year and hence can be utilized directly or indirectly. Directly can be used by photosynthesis or converting it into electricity using solar photovoltaic (SPV) modules. Basically three different technologies viz. Mono-crystalline silicon (m-Si), multi-crystalline silicon (mc-Si) and ribbon silicon based SPV modules are present in the market. In general it has been found that the mono-crystalline-silicon wafer is more expensive than that of multi-crystalline-silicon wafer and as far as the efficiency is concerned, m-Si based module is better than mc-Si module [2]. The conversion efficiency of commercial types of mc-Si cells are found to be in the range of 12–15%, however, it can be enhanced up to 20% by using more sophisticated solar cell designs [3]. Indirectly it can be

used by heating the medium using solar collectors for low/medium temperature heating applications such as solar dryer, solar water heating and solar cooking. However, the use of solar energy for drying application is very important for food grain/products for their safe storage to maintain the quality and nutrient values.

The solar dryer is an energy efficient option in the drying processes and the use of forced convection solar driers seems to be an advantage as compared to the traditional methods because it improves the quality of the product considerably [4–9]. Also, the use of solar energy for low temperature applications such as water heating is the most common application around the globe. There are different types of solar water heaters (SWH) having flat plate collector (FPC), evacuated tube collector (ETC) and compound parabolic collectors (CPC). In recent years, a few authors have studied different features of solar collector systems using various approaches [10–15]. For example, Kurtbas and Durmus [10] have studied the solar air heater for different heating purposes whereas, Luminosu and Fara [11] and Torres-Reyes et al. [12] have studied the optimal thermal energy conversion and design of a flat plate solar collector using exergy analysis. Dharuman et al. [13] designed, fabricated and carried out the experimental study of water heating device under various operating conditions. Nahar [14] carried out the comparative analysis of Cu–Al fin with Cu–Cu fin in flat-plate collectors to test solar water heater. Shukla et al. [15] investigated the performance of thermal energy storage based solar water heater. Rakesh and Rosen [16] studied the thermal performance of an integrated solar water heater with a corrugated absorber surface.

Solar energy can also be utilized for medium/higher temperature applications such as cooking of food using solar cookers and power generation by using solar concentrating collectors. Solar cooking saves not only fossil fuels but also keeps the environment free from pollution without affecting the nutritional value of the food [17]. As solar cookers utilize direct solar radiation as a fuel, which is intermittent in nature and available in day time only, it is important to explore other renewable energy sources to assist the cooking such as biomass for cooking applications. Biomass based cooking devices such as, cookstove (chulha), which has been used by the people for the last few centuries, is an option during the late evening hours and/or night time. Most of the households in rural areas of developing countries still use biomass as fuel for cooking and heating purposes [18]. Different types of biomasses such as, wood, crop residues, cattle dung and charcoal have been utilized for cooking and heating applications around the world for centuries [19]. Census data 2001 [20] indicated that the traditional energies is being used by approximately 72% of the population of India for their cooking needs, of which over 89% of this population lives in rural areas [21].

This paper presents an extensive literature survey on energy and exergy analyses of typical renewable energy systems such as solar air heater, solar water heater, solar cooker, solar photovoltaics and biomass cookstoves. The main idea was to get thrust and scant area of exergy analysis of renewable energy systems and have possible future direction of research for readers.

2. Solar thermal systems

The solar thermal systems as specified by their applications are those systems which convert solar energy into heat through special devices known as collectors for useful applications. This section presents the details on different solar thermal systems, such as, solar air heater, solar water heater and solar cookers for useful applications as given below:

2.1. Solar air heater

Solar air heaters are important devices in which the ambient air is used as the circulating media/fluid for air heating, space air-conditioning, and crop drying applications by directly using the solar energy. The heat collected through these devices could be used in different ways [4–9]. Ozturk and Demirel [22] experimentally investigated the thermal performance of a solar air heater having its flow channel packed with Raschig rings based on the energy and exergy analyses. The average daily net energy and exergy efficiencies were found to be 17.51 and 0.91%, respectively. Potdukhe and Thombre [23] designed, fabricated and studied a solar dryer fitted with a novel design of absorber having inbuilt thermal storage capabilities using simulation approach. MacPhee and Dincer [24] carried out the detailed thermodynamic analysis of charging of an encapsulated ice thermal energy storage device (ITES) through heat transfer analysis.

2.1.1. Energy analysis

For steady state operation, neglecting the change in kinetic and potential energy, the mass and energy balance for the solar air heater can be written as below [22–24]:

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_o \left(h_o + \frac{V_o^2}{2} \right) - \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} \right) \tag{2}$$

Also the solar energy incident on the collector surface is given by [22–24]

$$Q_c = AI_s \tag{3}$$

where A is the area of collector exposed to the sun light and I_s is the intensity of solar radiation at a particular location. The energy collected from the collector can be written as [22–24]

$$Q_u = \alpha\tau I_s A \tag{4}$$

where α is the absorptance of glass and τ is the transmittance of outer surface of the collector. Again, the useful energy transmitted into the collector is absorbed by the circulating fluid/air, and can be written as below [22–24]

$$Q_u = Q_f = \dot{m}_f C_{p,f} \Delta T \tag{5}$$

where C_{pf} and $\dot{m}_f$ are, respectively the specific heat and mass flow rate of the circulating air/fluid, ΔT is the temperature difference and Q_f is the heat absorbed by the fluid. Thus, the energy efficiency (η) of the system can be written as [25]

$$\eta = Q_f / Q_c = \dot{m}_f C_{pf} \Delta T / AI_s \tag{6}$$

2.1.2. Exergy analysis

Exergy balance equation for solar air heater systems can be written as below [5,26–34]:

$$Exergy = (u - u_\infty) - T_\infty(s - s_\infty) + \frac{P_\infty}{J}(v - v_\infty) + \frac{V^2}{2gJ} + (z - z_\infty)\frac{g}{g_c J} + \sum_c (\mu_c - \mu_\infty) N_c + E_i A_i F_i (3T^4 - T_\infty^4 - 4T_\infty T^3) + \ldots \tag{7}$$

where $(u - u_\infty)$ is the internal energy, $T_\infty(s - s_\infty)$ is the entropy, $(P_\infty/J)(v - v_\infty)$ is the work done on/by the systems, $(V^2/2gJ) + (z - z_\infty)(g/g_c J)$ is the momentum, $\Sigma_c(\mu_c - \mu_\infty)N_c$ is the gravity, $E_i A_i F_i (3T^4 - T_\infty^4 - 4T_\infty T^3)$ is radiation emission and subscript ∞ presents the reference condition. Again, neglecting the change in the gravitational force, momentum, and pressure, Eq.(7) can be

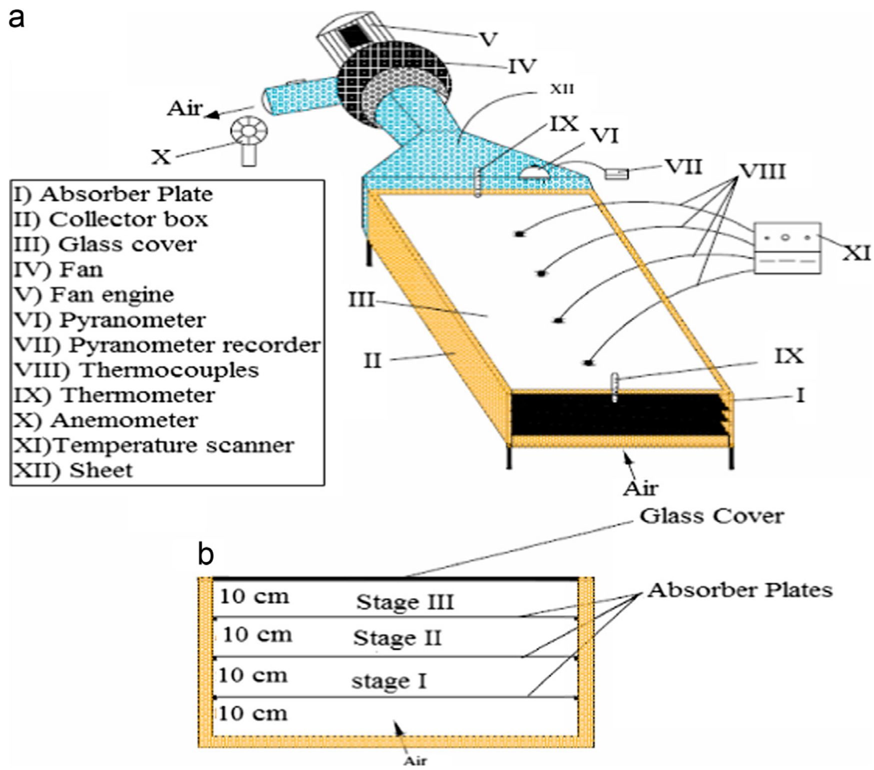


Fig. 1. Schematic assembly of the (a) SAH system and (b) front view of the collector [41].

re-written as below [5,28–34]:

$$Exergy = \bar{c}_p\left[(T - T_\infty) - T_\infty \ln\frac{T}{T_\infty}\right] \quad (8)$$

The exergy received by collector is given by [28–34]

$$Ex_c = Q_C(1-(T_a/T_S)) \quad (9)$$

where T_a is ambient temperature, and T_S is the temperature of the source while, the exergy received by fluid is written as [28–34]

$$Ex_f = \dot{m}(E_O - E_i) = \dot{m}[(h_O - h_i) - T_a(s_O - s_i)] \quad (10)$$

where h denotes the specific enthalpy, s denotes the entropy and $\dot{m}$ denotes the mass flow rate while i and o stand for input and output. The output specific enthalpy of the fluid is given by [32–34]

$$h_o = C_{Po}T_O \quad (11)$$

where T_O is outlet temperature, and C_{Po} is the specific heat of air at outlet. The specific enthalpy of inlet air is given by [32–34]

$$h_i = C_{Pi}T_i \quad (12)$$

where C_{Pi} is input specific heat, T_i is inlet temperature while the entropy difference can be calculated using the below equations [32–34]:

$$C_{P_i} = a + kT_i \quad (13)$$

$$C_{P_o} = a + kT_O \quad (14)$$

$$ds = dq/T = C_p dT/T = (a+bT)(dT/T) = adT/T + kdT \quad (15)$$

Using Eqs. (13) and (14), the values of constants a and k can be calculated, which on substituting into Eq. (15), may give the entropy difference. Thus the exergy efficiency of the solar air heater can be given as [28–34]

$$\psi = Ex_f/Ex_C = \dot{m}[(h_O - h_i) - T_O(s_O - s_i)]/Q_C(1 - T_O/T_S) \quad (16)$$

where Ex_C is the exergy received by collector, Ex_f is the exergy received by the fluid.

2.1.3. Case studies

Enibe [35] designed, fabricated and evaluated a passive solar powered air heating system based on the exergy analysis. The system consisted of a single-glazed flat plate solar collector integrated with a phase change material (PCM) based heat energy storage system. The experiments were carried out under the typical climatic conditions of Nsukka (Nigeria) in the daytime with no-load conditions. In this experimental study, data for different parameters such as ambient temperature and solar radiation were collected and found to be varied in the range of 19–41 °C and 4.9–19.9 MJ/m^2 respectively. The peak cumulative useful efficiency was calculated and found to be about 50% while peak temperature rise of the heated air was found to be about 15 °C. The system has been found suitable for the use as a solar cabinet crop dryer for plants which do not require direct exposure to the sunlight such as aromatic herbs and medicinal plants. Kurtbas and Durmus [36] designed a new type of solar air heater and evaluated it using exergetic analysis. They used five solar collectors with dimensions of 0.9 × 0.4 m and were set to four different cases. They found that the efficiency of the collector increases with the increase of mass flow rate which is due to the increased heat transfer to the air flow. They suggested that the collector efficiency, the inlet and outlet temperature difference of the air geometry and pressure loss etc. are some of the more important parameters for evaluating the performance of a solar collector.

Ajam et al. [37] worked on the optimization of the solar air heater based on the exergetic analysis. For this purpose, an integrated mathematical model of thermal and optical performance of the solar heater has been derived. The overall thermal loss coefficient and other heat transfer coefficients of the heater

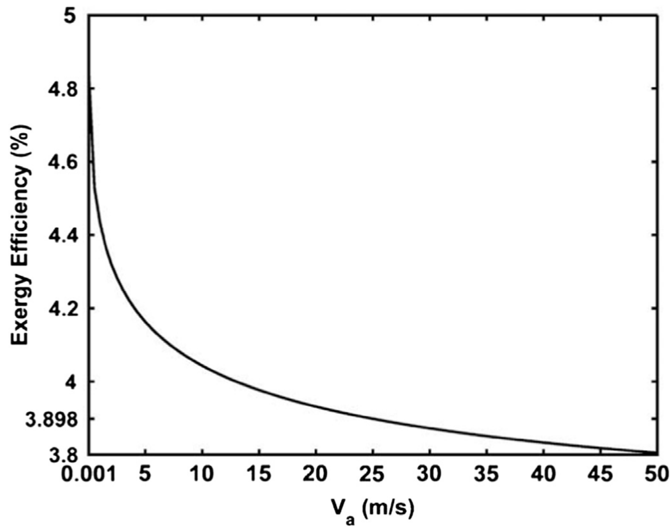


Fig. 2. The variations of the exergy efficiency versus the wind speed [44].

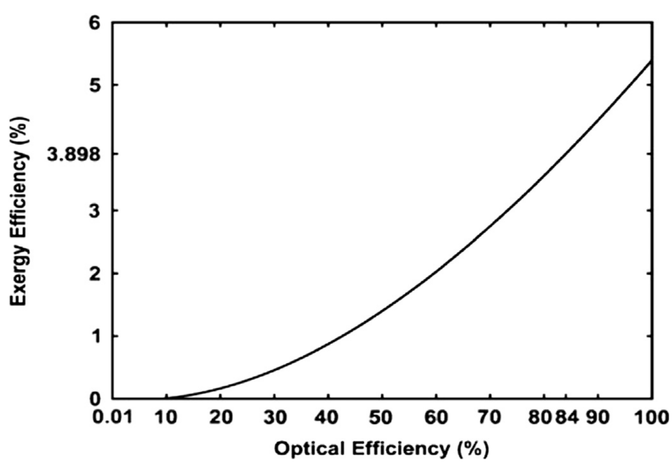


Fig. 3. The variations of the exergy efficiency versus the optical efficiency [44].

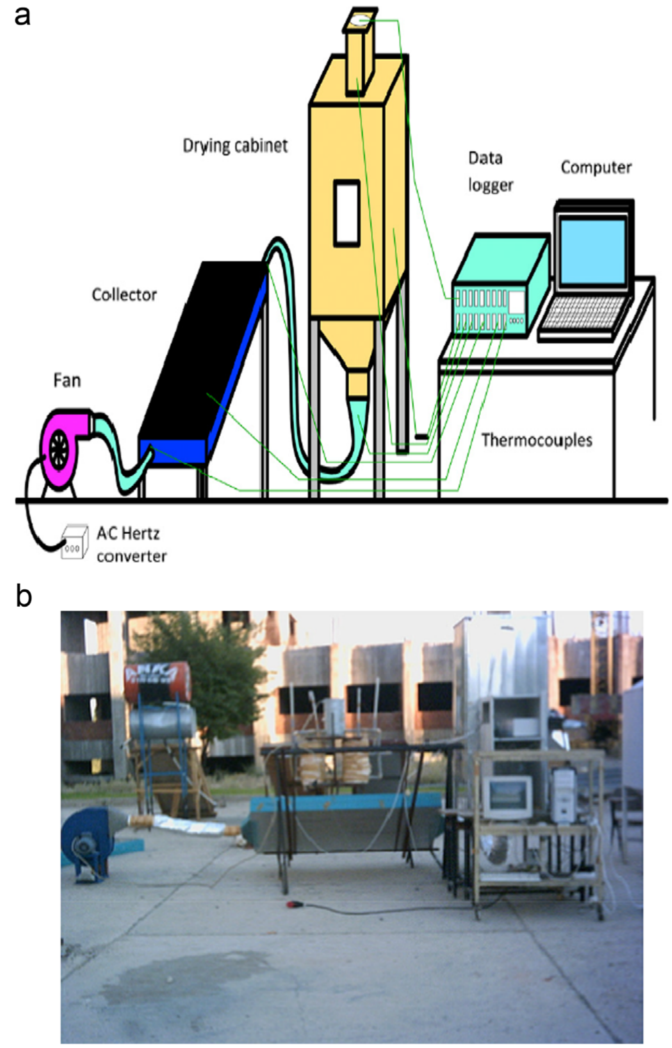


Fig. 4. (a) Schematic and (b) photographic view of the solar dryer system [45].

were assumed to be variable. Using MATLAB toolbox the exergy efficiency equation has been optimized and compared with the thermal efficiency of the heater, which ultimately resulted in the increase of exergy efficiency. They concluded that the exergy analysis is a better method for design, development and optimization of solar air heaters. This was shown due to the fact that exergy efficiency is a proportion to common quantities in solar engineering such as, thermal efficiency, temperature, pressure drop, mass flow rate of fluid etc. and other important parameters. Kurtbas and Turgut [38] investigated the solar air heater with free and fixed fins using exergy analysis. In this study each of the fins with rectangular shape was having two different surface areas and located on the absorber surface in free and fixed manners. In the free fins type model, the fins were located on the absorber surface in a way that they are able to move freely, while in the fixed fins type model fins were fixed to the absorber surface. They revealed that the fins located in flow area enhance the heat transfer coefficient and outlet temperature of the air due to which the collector efficiency enhanced. They also found that, both the heat transfer and exergy loss enhanced due to increase in pressure drop and also the loss ratio affected slightly with the pressure drop inside the air heater.

The solar air collectors with the passive augmentation techniques using exergetic analysis were studied by Ucar and Inallı [39]. In order to provide a better heat transfer surface suitable for the passive heat transfer augmentation techniques, different shape and arrangement of the absorber surfaces in the collectors were reorganised. The performance of such solar collectors with staggered absorber sheets and attached fins on the absorber surface were analysed and tested experimentally. It was found that the efficiency of solar collector has increased approximately by 10–30% using the passive techniques as compared to the conventional solar collector. Koca et al. [40] investigated the flat-plate solar collector with phase change material (PCM) using energy and exergy analyses. They used calcium chloride hexahydrate ($CaCl_2.6H_2O$) as the PCM in the thermal energy storage (TES) system while the solar energy collection and storage units were combined into a single unit. The experiments were carried out for 3 different days in the month of October at a typical location. From the measured data experimental it was found that the stored and instantaneous solar radiation exhibits a bell-shaped variation during all experimental days. The exergy efficiencies of latent heat storage systems were found very low which was due to the fact that the temperatures of the storage material and ambient were close to each other.

Esen [41] carried out the energy and exergy analysis of a novel flat plate solar air heater (SAH) with and without obstacles. In this study, the experiment was carried out by varying the mass flow rate of air at different levels of absorbing plates in the flow channel duct. The schematic view of the double flow SAH system and front view of the collector are shown in Fig. 1(a) and (b) respectively.

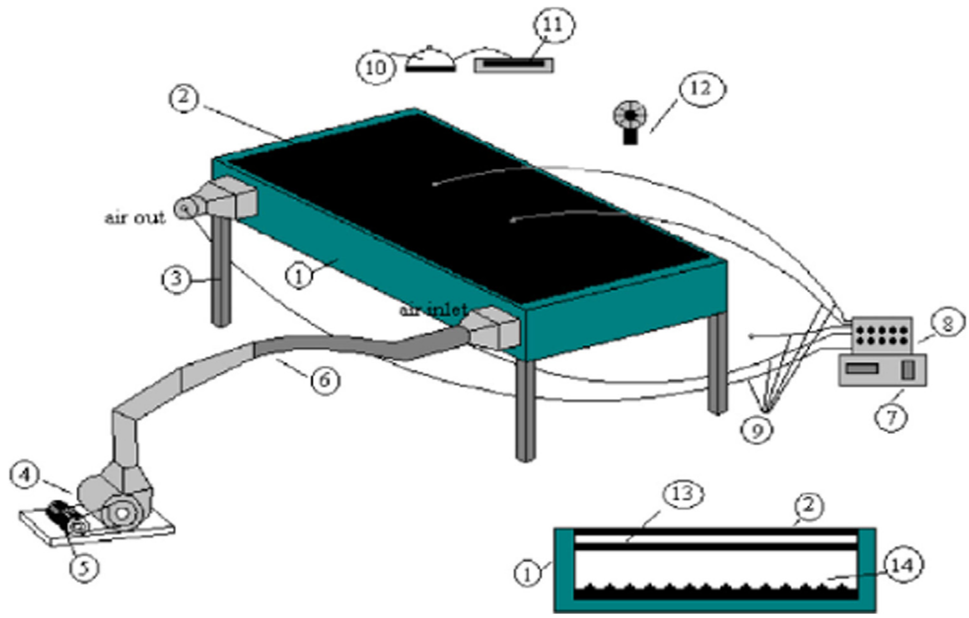


Fig. 5. Schematic view of experimental set-up. (1) Collector box, (2) glass cover, (3) foot, (4) fan, (5) fan engine, (6) connection pipe, (7) channel selector, (8) digital thermometer, (9) thermocouples, (10) pyranometer, (11) pyranometer recorder, (12) anemometer, (13) absorber plate (cooper plate that has been painted black) and (14) absorber plate with obstacles [46].

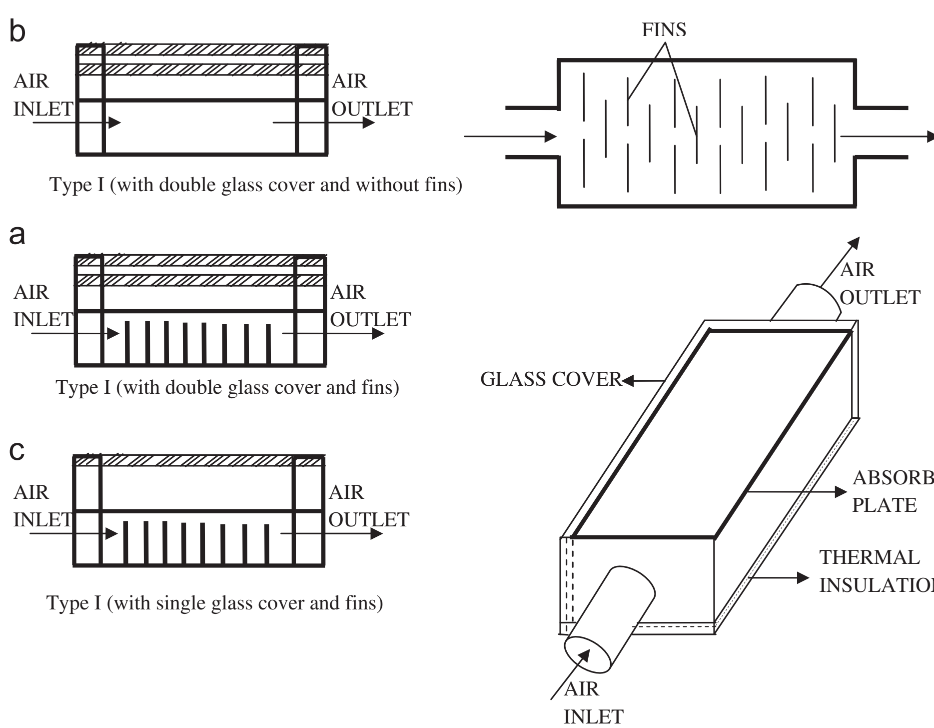


Fig. 6. Construction details of Type I, II and III [47]: (a) TYPE I (with double glass cover and without fins), (b) TYPE II (with double glass cover and without fins) and (b) TYPE III (with single glass cover and without fins),

Based on the analysis, it was found that the optimal value of efficiency lies in the middle level of the absorbing plate in the flow channel duct for all the operating conditions. The efficiencies for double-flow collector with obstacles were found to be 60.97%, for 0.025 kg/s which is better than that without obstacles having efficiency of 25.65%, for 0.015 kg/s. The comparative study of various types of solar air heater having geometry with artificial roughness in the absorber plate of duct based on energy and exergy efficiencies was presented by Gupta and Kaushik [42]. They found that the artificial roughness on absorber surface is a better option to enhance the efficiencies in comparison to the smooth surfaces. The energy and exergy efficiencies were analysed for different artificial roughness geometries such as, smooth surface, circular ribs, V shaped ribs, wedge shaped rib, expanded metal mesh, rib-grooved and chamfered rib-groove. Both the efficiencies were found to be higher for smooth surface, while lowest for chamfered rib-groove. However, these trends were found to be in the reversed order for very high Reynolds number. For example the exergy efficiency were found to be in the similar trend as energy efficiency for medium Reynolds number while they were found to be in the reverse order for relatively lower Reynolds number.

Ozgen et al. [43] studied on a flat-plate solar air heater with an absorbing plate made of aluminium cans into the double-pass

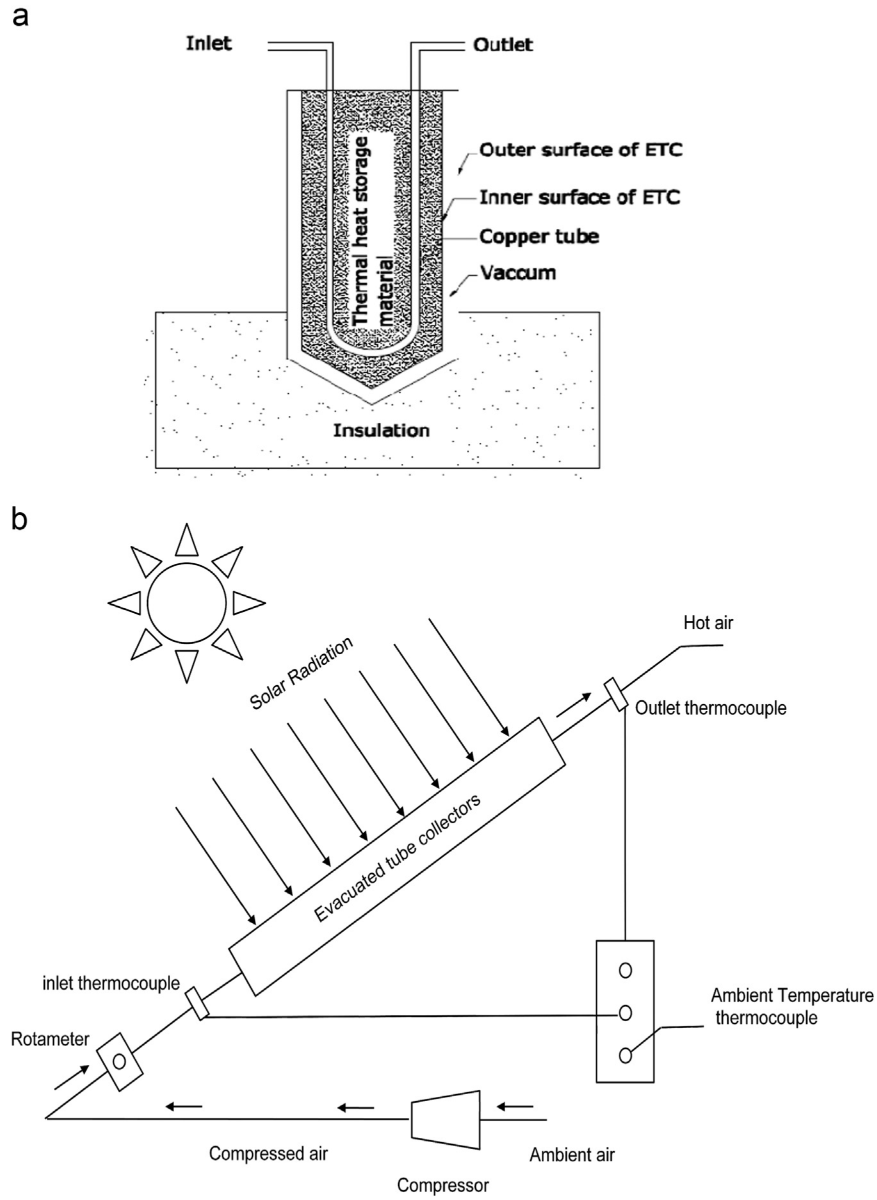


Fig. 7. (a) Cross-sectional view of ETC tube with TES and (b) schematic of the experimental set-up [50].

channel using three different absorber plates. In Type I, cans were arranged in zigzag manner on the absorber plate while in Type II they were arranged in order. On the other hand, the plate was kept without cans for type III model. The experiments were performed for two different air mass flow rates of 0.03 kg/s and 0.05 kg/s, respectively. The double-flow type of the solar air heater with aluminium cans, having more heat-transfer area achieved higher thermal efficiency. Farahat et al. [44] worked on the exergetic optimization of flat plate solar collector using a simulation program. It was found that the optical efficiency has a great effect on the exergy efficiency as can be seen from Fig. 2. Also it was observed that the energy efficiency increases without extremum points with operating parameters but the absence of such maximum points has created difficulties in the design of flat plate solar collectors. The exergy efficiency was found to be decreasing function of the ambient temperature and the wind speed as can be seen in Fig. 3.

The energy and exergy analyses of the thin layer drying process of mulberry via forced solar dryer were carried out by Akbulut and Durmuş [45]. The schematic diagram along with the photographic view of the solar drying system is shown in Fig. 4(a) and (b), respectively. The experiments were carried out for different mass flow rates varying between 0.014 kg/s and 0.036 kg/s. Based on the experimental data the exergy losses were calculated and found to be of 10.82 W, 6.41 W, 4.92 W, 4.06 W and 2.65 W with the drying mass flow rate varying in the range, mentioned above. However, the values of energy utilization ratio were found to be 55.2%, 32.19%, 29.2%, 21.5% and 20.5% for five different drying mass flow rates. It was also found that the exergy loss decreases with the increase in the mass flow rate of the drying air and the maximum exergy losses occurred at 0.014 kg/s flow rate. Akpinar and Kocyig˘it [46] designed, fabricated and experimentally investigated a new type of solar air heater with and without obstacles. The schematic diagram of the experimental set-up can be seen in Fig. 5. The experiments were carried out at two different air mass flow rates of 0.0074 and 0.0052 kg/s. From the experimental study, it was found that the efficiency of the solar air collectors depends on different parameters such as, solar radiation, geometry of the collectors and extension of the air flow line. The energy efficiency was found to be varying between 20% and 82% while, the exergy efficiency varied

from 8.32% to 44% at the same set of operating conditions. The highest efficiency was found to be for the solar air heater (SAH) with absorbent plate in the flow channel duct, whereas the lowest values were obtained for the SAH without obstacles for the same set of operating conditions.

Alta et al [47] investigated the energy and exergy efficiency of three different types of solar air heaters with different design features, one without fins and two with fins. The technical specification and other details of different types of heaters are shown in Fig. 6. The output energy and exergy rates of these heaters were evaluated at different flow rates of 25, 50 and 100 m^3/m^2 h having tilt angle of 0°, 15° and 30°, respectively. The heater having double glass cover with fins was found to be more effective which is due to the higher temperature gradient. Ezan et al. [48] has investigated the energetic and exergetic performances of a latent heat energy storage system based on the shell and-tube arrangement during charging and discharging processes of the storage material. The experimental system consists of a heat exchanger section, a measurement system and flow control systems. The inlet temperature varied from −5 °C to −15 °C for the charging mode, and the volumetric flow rates varied from 2 to 8 L/min. The experiments were performed for three different tube materials such as copper, steel and PE32 having two different shell diameters of 114 mm and 190 mm, respectively. They concluded that the exergetic efficiency increased with increasing inlet temperature and flow rate during charging period.

Prommas et al. [49] carried out the energy and exergy analyses of drying process in porous media using hot air. The objective of the study was to find out the exergy input and the distributions of the exergy losses of the different drying operations, the exergy losses of two operations porous packed bed and the effect of operating parameters on the exergy losses. The exergy efficiency was found to be increasing function of drying time which was due to the fact that the available energy enhanced in the drying chamber. They also found that the exergy efficiency of C-bed was significantly higher than that of the F-bed after 60 min of drying time. A comparative study on evacuated tube collector based solar air heater with and without thermal energy storage (TES) was carried out by Tyagi et al. [50] using exergy approach. In this study, they used total 12 numbers of ETC tubes having three different arrangements viz. four tubes having hytherm oil, four having paraffin wax and four tubes without any storage material. The experimental set-up used in the study is shown in Fig. 7(a and b). The experiments have been carried out at different mass flow rates of 10, 20, 30, 40 and 50 LPMs. Both the efficiencies of the system was found to be increasing with time, attains its peak generally in the first half and then decreases afterwards without TES. On the other hand with TES both the efficiencies increase with time, attain their peaks at approximately 16:30 h with a small fluctuation with flow rate and then decrease smoothly. It was also found that both the efficiencies are higher in the cases with TES than those without TES however; both the efficiencies in the case of paraffin wax were found to be slightly higher than those with hytherm oil.

A compact literature survey on energy and exergy analyses of solar drying systems was carried out by Panwar et al. [51]. They suggested that using solar energy for low grade temperature applications for example for drying agricultural products is the promising option. The exergy efficiency was found to be as actual efficiency of the process due to irreversibility associated with the system. Therefore, it can be said that exergy analysis is a tool to access the efficient usage of solar energy. It is the property of the system, which gives the maximum power that can be obtained from the system when it is brought to a thermodynamic equilibrium state from a reference state. The energy used in drying of agricultural and industrial produce is significant and, therefore, represents an often reducible element of process cost. Saidur et al. [52] presented the literature survey on exergy analysis of solar energy applications such as solar photovoltaic, solar pond and solar air conditioning. From their study, it was found that the thermal efficiency is not the only parameter to guide the selection of a system to get the desired output. Therefore it was suggested that the concept of exergy may guide for specific design of system for better performance. The highest exergy destruction was observed in solar collector subsystem in most of the heating and cooling devices. Increasing the mass flow rate leads to an increment in the exergetic efficiency in photovoltaic thermal (PV/T) systems.

Aghbashlo et al. [53] presented the literature review on exergy analysis of drying process and subsystems. They found that the concept of exergy has been applied to many drying systems based on demonstration projects. However, exergy analysis of other renewable energy drying systems such as photovoltaic based solar dryer, hybrid with geothermal or waste waters and solar dryer with thermal energy storage has not been carried out yet. Oztop et al. [54] carried out the literature survey on exergetic aspects of solar air heater. They found that the work on the performance of solar air heaters using exergy analysis is less explored. Benli [55] studied the solar air heaters having different roughness geometries using exergy analysis. Heat transfer and pressure loss was found to be increasing with the increase in surface roughness of collector. It was also found that as the collector efficiency increases, exergy loss decreases.

2.2. Solar water heater

Solar water heaters are the natural and carbon free process to get hot water for many useful applications such as, domestic, industrial and commercial applications. A solar water heater basically consists of a collector and insulated storage; collector is used for collecting solar radiation from sun and storage tank for storing the hot water. Basic functioning of solar water heater is that solar energy from the sun incident on the absorber panel coated with selected coating transfers the heat to the water flowing through the tubes and the water passing through the tube gets heated which is finally delivered to the storage tank. In general, the temperature of water goes upto 60–70 °C on a good sunny day and is useful for many real life applications.

2.2.1. Energy analysis

The general energy balance equation of the solar water heater may be given as below [56]:

$$Q_c = Q_w + Q_b + Q_L \tag{17}$$

where Q_c denotes the energy absorbed by the collector, Q_w denotes the energy stored in the storage tank, Q_b denotes the energy stored in the body and Q_L denotes the energy lost. Therefore useful energy is given by

$$Q_w = Q_c - Q_b - Q_L \tag{18}$$

The useful energy gained by water in the tank is given by [56]

$$Q_w = m_w C_{pw}(T_f - T_i) \tag{19}$$

Using the above equation, Q_b and $Ex_i = i\left[1+\frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]A_{SC}$ can also be written as

$$Q_b = m_b C_b (T_{fb} - T_{ib}) \tag{20}$$

$$Q_L = U_t (T_{m,st} - T_a) \tag{21}$$

where U_t denotes the coefficient of total heat loss rate, $T_{m,st}$ is the mean system temperature which can be expressed as below [56]:

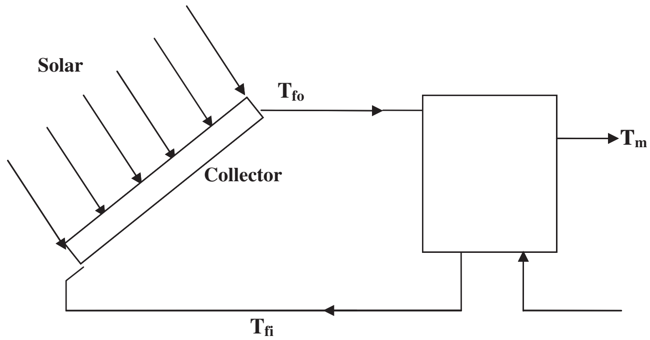


Fig. 8. A typical domestic scale solar water heater [60].

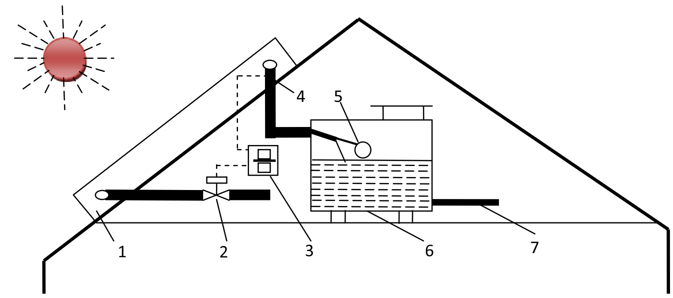


Fig. 9. Temperature controlled solar water heater [56]. (1) Collector (2) selonoit valve and cold water supply (3) process control equipment (4) temperature sensor and hot water outlet (5) float control (6) hot water tank and (7) hot water outlet.

$$T_{m,st} = \frac{T_{ib} + T_{fb}}{2} \tag{22}$$

Using Eqs.(3) and (19) the energy efficiency of the solar water heating system can be written as [56]

$$\eta = \frac{m_w C_{pw}(T_f - T_i)}{I_s A} \tag{23}$$

2.2.2. Exergy analysis

The exergy analysis can be performed based on the configuration of solar water heater. The exergy received by collector is given by [57,58]

$$Ex_c = I_s A[(1-(T_a/T_s)] \tag{24}$$

where T_a is ambient temperature, and T_s is the temperature of the sun while, the exergy received by fluid is written as [57,58]

$$Ex_f = \dot{m}(E_O - E_i) = \dot{m}[(h_O - h_i) - T_a(s_O - s_i)] \tag{25}$$

where $\dot{m}$ is volume flow rate of water circulating through the collector tubes, h_i is input specific enthalpy, and s_i is input entropy, whereas h_O is output specific enthalpy, s_O is output entropy, respectively and are given as below:

$$h_O - h_i = C_{p,w}(T_o - T_i) \tag{26}$$

and

$$s_O - s_i = C_{p,w} \ln\left(\frac{T_o}{T_i}\right) \tag{27}$$

However, the exergy received by fluid can also be given by

$$Ex_f = \dot{m}C_{p,w}(T_O - T_i)\left(1 - \frac{T_a}{T_f}\right) \tag{28}$$

The exergy efficiency of the system can be written as [57,58]

$$\psi = E_f/E_C = \frac{\dot{m}[(h_O - h_i) - T_O(s_O - s_i)]}{Q_u(1 - T_O/T_S)} \tag{29}$$

Using Eq. (28), the exergy efficiency can also be given by

$$\psi = \frac{\dot{m}C_{p,w}(T_O - T_i)(1-(T_a/T_f))}{I_s A[(1 - T_O/T_S)]} \tag{30}$$

2.2.3. Case studies

The characteristics of evacuated tube based solar water heater were evaluated by Morrison et al. [59]. Assuming that there was no interaction between the adjacent tubes in the collector array, they developed a numerical model for heat transfer and fluid flow inside a single ended evacuated tube. The computational domain used in this study was single-ended thermosyphon with a constant pressure condition applied across the open end. The experimental and simulation results showed that there was a good agreement in a number of qualitative and quantitative parameters, such as, the location of the peak velocity, the peak velocity of the heated fluid stream, the cross-over point between the two opposing streams and the flow structure etc. Xiao and Ben [60] evaluated the performance of domestic size solar water heater based on the exergy analysis. The schematic diagram of the experimental set-up is shown in Fig. 8. From the study, it was found that the proper insulation of collector and storage tank is very important because exergy losses due to imperfect thermal insulation in collector and storage tank is significant and cannot be ignored.

Luminosu and Fara [61] determined the optimal operation mode of flat plate collector using exergy analysis through simulation. The statistical data for the solar radiation of a given area was used and the optimal values for the characteristic quantities of the flat-plate solar collector were obtained by developing the exergy analysis for the selected models. Budihardjo et al. [62] developed a correlation for natural circulation flow rate through single ended water-in-glass evacuated tubes mounted over a diffuse reflector. It was found that when the heat input was concentrated on the top circumference of the tube, the effect of circumferential heat flux distribution on the circulation flow rate through the tubes was not significant. Therefore, the correlation could be used to predict the flow rate at any time of the day. Different flow structures were observed in the tube when a concentrating reflector was used underneath the collector.

Gunerhan and Hepbasli [63] carried out the performance evaluation of solar water heating system based on exergy analysis under the typical climatic condition of Izmir province (Turkey). They analysed different components of the system viz. the flat plate solar collector, heat exchanger (storage tank) and the circulating pump. The exergy efficiency on a product/fuel basis was found to be varying between 2.02% and 3.37% for the solar collector, 16% and 51.72% for the heat exchanger and 10% and 16.67% for the circulating pump. However, for overall system, the exergy efficiency was found to be in the range of 3.27–4.39%. The performance evaluation of two different types of solar collector's viz. glazed flat plate collector and an evacuated tube solar collector were studied by Zambolin and Del Col [64] using energy analysis. Both the collectors were installed in parallel and tested for the same working conditions. Also the evacuated collector was a direct flow type with external compound parabolic concentrator (CPC) reflectors. It was also found that the daily efficiency can be estimated by using the parameters of the quasi-dynamic model. The optical efficiency of the flat plate collector (FPC) during the morning and afternoon hours was found to be decreasing due to higher reflection losses and lower intensity of solar radiation. However, the efficiency loss reduced in the vacuum tube collector because of its geometry and hence the efficiency of ETC based system was found to be higher than that of the FPC system.

Two different types of evacuated tube solar collectors viz. water-in-glass tubes and the heat-pipe designs were studied by

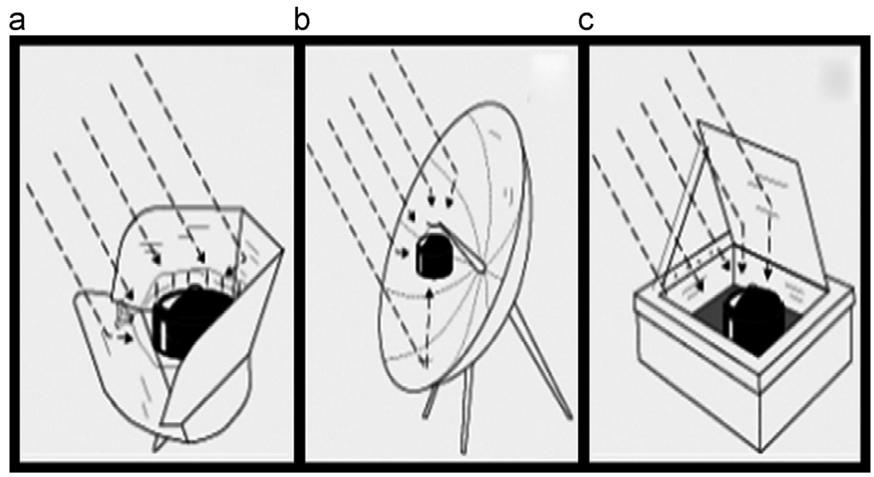


Fig. 10. Types of solar cookers: (a) solar panel cooker; (b) solar parabolic cooker; and (c) solar box cooker [68].

Hayek et al. [65] using exergy analysis. Total 20 numbers of evacuated tubes along with a tank and a circulation system with measurement tools, was constructed and used for the experimental observation. The experiment was performed from November to January. The experimental study showed that the performance of ETC with heat pipe design was better than that of water-in-glass design and the efficiency in the former case was found to be almost 15–20% higher than that of the later. However, the payback period of the former was found to be much longer than the later owing to the higher investment cost. Ayompe et al. [66] carried out the performance evaluation of two different types of solar water heaters such as, the flat plate collector (FPC) and heat pipe evacuated tube collector (ETC) in the climatic condition of Dublin (Ireland). The energy analysis on daily, monthly and yearly basis was carried out and the performance of the above mentioned systems were compared. Total 1984 kWh and 2056 kWh of heat energy were collected using 4 m^2 FPC and 3 m^2 ETC systems, respectively, for an annual solar radiation of 1087 kWh/m^2. The annual average collector efficiency was found to be 46.1% and 60.7%, while the system efficiency was found to be 37.9% and 50.3% for the FPC and ETC, respectively. Also both the systems were found to be economically unviable as the payback period was found to be 13 years and 48.5 years for FPC and ETC respectively.

Gang et al. [67] represented the performance evaluation of compound parabolic concentrator type solar water heater with a U-pipe under the typical climatic condition of Hefei, in the eastern region of China based on energy and exergy analysis. They found that when the water temperature was heated from 26.9 °C to 55 °C, 65 °C, 75 °C, 85 °C, and 95 °C, the thermal efficiency was found to be a decreasing function. In other words, the lower thermal efficiency has been found at 95 °C and found to be above 49%. The exergetic efficiency has been found to be increasing in nature i.e. the highest efficiency was found to be at 55 °C and found to be always above 4.62%. Ceylan [56] developed and studied a new temperature controlled solar water heater (TCSWH) as shown in Fig. 9 based on energetic and exergetic analyses. The experiments were carried out at 40 °C, 45 °C, 50 °C and 55 °C and the same was compared with the thermosiphon system. The highest amount of water had been found to be 108 kg by setting the control device at 40 °C. The average energetic efficiency was found to be 65% for the TCSWH and 60% for the thermosiphon system respectively and hence, the TCSWH was found to be better than the thermosiphon system for the same set of operating parameters.

2.3. Solar cooker

There are a number of solar cookers developed by many researchers and manufacturers from all over the world. Solar cookers may be classified basically in three different categories such as solar panel cookers, solar box cookers and solar parabolic cookers which can be seen in Fig. 10 [68]. The standard proposed by Mullick et al. [69] is more complicated and less universal than the one being evaluated, though the characteristic curve they developed is a good predictive tool. Grupp et al. [70] employ a test procedure that presents much useful information especially, for Europe. In recent years several authors have investigated the methodologies being used for the evaluation and comparison of solar cookers [71,72]. Traditional methods of characterizing the performance of solar cookers are based on energy analysis [73,74] and are based on the first law of thermodynamics, so they provide information about the total quantity of energy without investigating the quality and the availability of energy. The exergetic analysis of low cost parabolic type and box type solar cooker was conducted by Ozturk [75] for the first time in 2004. Inspired from the study of Ozturk [76], Petela [77] in 2005 carried out the performance evaluation of a cylindrical trough shape solar cooker based on the exergetic analysis. The comparative study on energy and exergy efficiency for Box type and parabolic type solar cookers was conducted by Oztruk [78] under the climatic conditions of Turkey.

Buddhi and Sahoo [79] designed a box-type solar cooker having latent heat storage and showed that it is possible to cook food, during the evening hours with latent heat storage. Nahar [80] designed, developed and tested a novel solar cooker that does not require any tracking and its performance was compared with a hot-box type solar cooker. The overall efficiency of the solar cooker was found to be 29.5% and the payback period was found to be between 1.30 and 3.29 years depending upon the fuel it replaces. Gaur et al. [81] presented the performance study of the box-type solar cooker with special emphasis on the shape of lid and utensils used. The study revealed that the performance of a solar cooker could be improved if a utensil with a concave shape lid is used instead of a plain lid, generally, provided with the solar cookers. Buddhi et al. [82] also analyzed the thermal performance of a box type solar cooker on the basis of first and second figure of merit with and without load, respectively and found that the second figure of merit depends on the quantity of water loaded in the solar cooker and emphasized that the test method should specify the amount of water to be taken.

2.3.1. Energy analysis

Energy output from the solar cooker can be given by

$$E_o = m_w.C_{pw}\lfloor (T_{wf} - T_{wi}) \rfloor / t \quad (31)$$

where m_w denotes the mass of water, C_{pw} denotes the specific heat of water, T_{wi} denotes inlet water temperature, T_{wf} denotes the final temperature of water inside the cooker. By Eqs. (3) and (31), energy efficiency of solar cooker may be given as below:

$$\eta = \frac{E_o}{E_i} = \frac{m_w.C_{pw}\lfloor (T_{wf} - T_{wi}) \rfloor / t}{I_s A} \quad (32)$$

2.3.2. Exergy analysis

For the steady-state flow process during a finite time interval, the overall exergy balance of the solar cooker can be written as follows:

$$(Exergy)_{in} = (exergy)_{out} + (exergy)_{loss} + irreversibility \quad (33)$$

The exergy of a solar flux with both beam and diffuse components can be represented by [79,83]

$$Ex_i = I_b[1 - (4T_a/3T_s)] + I_d[1 - (4T_a/3T_s^*)] \quad (34)$$

where $\dot{E}x_{therm}$ is the exergy of solar radiation (W/m^2); I_b is the intensity of beam radiation (W/m^2); I_d is the intensity of direct radiation (W/m^2); T_a is the ambient temperature (K); T_s is the sun temperature (K); and T_s^* is the effective diffuse radiation temperature (K). The exergy input to the solar cooker can also be given as below [84,85]:

$$Ex_i = i\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] A_{SC} \quad (35)$$

The exergy content of water (ε) at temperature T_i can be calculated by

$$\varepsilon(T_i) = m_w.C_{pw}\left[(T_{wi} - T_o) - T_o \ln \frac{T_{wi}}{T_o}\right] \quad (36)$$

But if the temperature of water is increased from T_{wi} to T_{wf}, the exergy content of water enhanced and is defined as

$$Ex_o = m_w.C_{pw}\left[(T_{wf} - T_{wi}) - T_a \ln \frac{T_{wf}}{T_{wi}}\right] \Big/ \Delta t \quad (37)$$

An exergy efficiency of the solar cooker can be given as below [86]:

$$\psi = \frac{Exergy\ output}{Exergy\ input} = \frac{Ex_o}{Ex_i} = \frac{m_w.C_{pw}[(T_{wf} - T_{wi}) - T_a \ln(T_{wf}/T_{wi})]/\Delta t}{i[1 + (1/3)(T_a/T_s)^4 - 4/3(T_a/T_s)]A_{SC}} \quad (38)$$

2.3.3. Case studies

The simple cylindrical trough shape parabolic type solar cooker was studied by Petela [73] using exergy analysis and the schematic diagram of the system is shown in Fig. 11. The detailed methodology for the exergy analysis of SPC and the distribution of the exergy losses had been presented in this study. From this study, it was observed that for the enhancement of the energetic and exergetic performance of the solar cooker, the optimization of

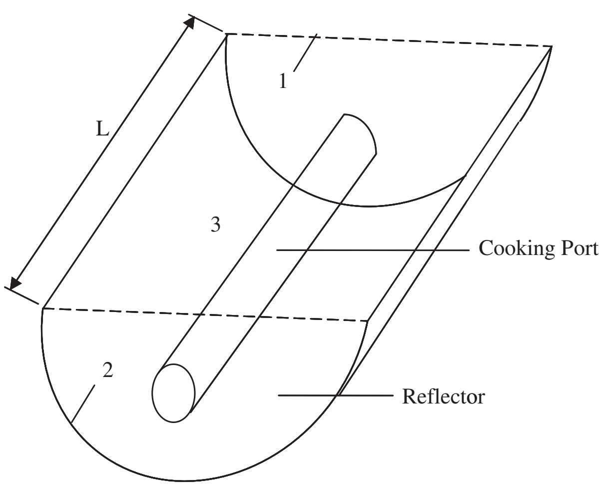


Fig. 11. The scheme of the SPC [73].

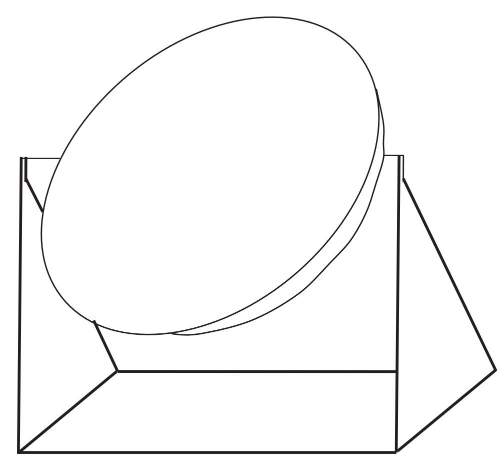


Fig. 13. Domestic-size solar cooker for outdoor cooking [87].

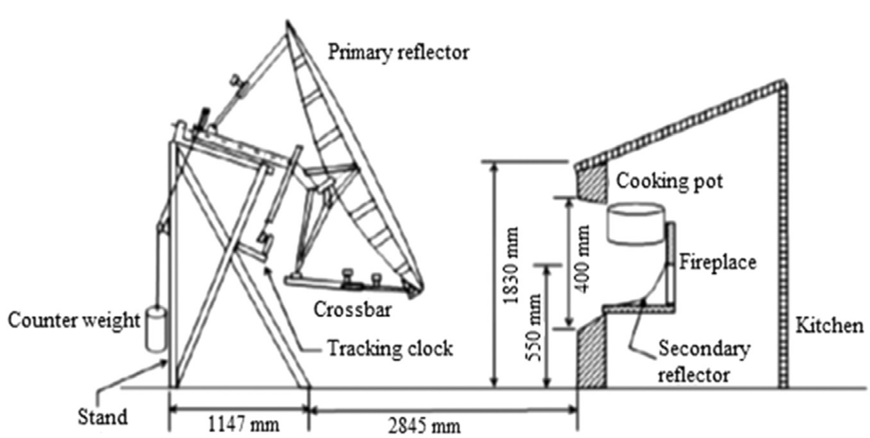


Fig. 12. Community-size solar cooker for indoor cooking [87].

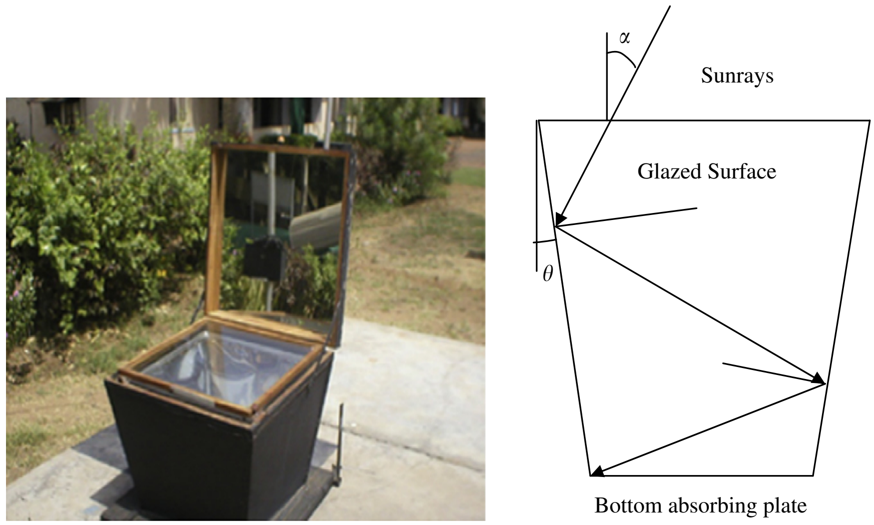


Fig. 14. Truncated pyramid type solar box cooker [90].

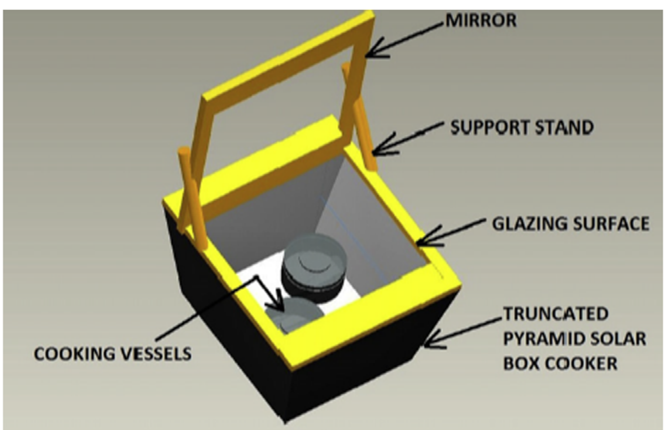


Fig. 15. The schematic diagram/model of TPSBC with cooking vessels [90].

different parameters is very important. The energy efficiency of the SPC was found to be in the range of 6–19% while the exergy efficiency was found to be below 1%. Kaushik and Gupta [87] studied the performance analyses of community-size and domestic-size paraboloidal solar cooker based on energy and exergy analyses. The schematic of community-size and domestic-size paraboloidal solar cooker are shown in Figs.12 and 13, respectively. They showed that the community-size solar cooker has the higher energy and exergy efficiencies and low characteristic boiling time as compared to the domestic-size paraboloidal solar cooker (DSC). In other words, the performance of CSC was found to be better than that of the DSC in all respect.

Mawire et al. [88] worked on the thermal energy storage (TES) system of an indirect solar cooker using simulated energy and exergy analyses using an oil-pebble bed as the TES material. Two different types of methods were used for energy and exergy analysis of TES system. For charging the TES, the flow rate of the circulating fluid was kept constant, while for discharging, it was varied. From their study it was found that the energy stored in constant temperature charging method was more than that of the constant flow rate charging method. The energy and exergy rates for the constant-temperature method were found to be slightly lower than those of the constant-flow rate method for lower solar radiation conditions. However, the best results for exergy rates and exergy efficiencies were obtained by using the constant-temperature method at high solar radiation conditions. Mawire et al. [89] also studied the mathematical models for thermal energy storage (TES) system and thermal energy utilization (TEU) system of an indirect solar cooker to perform the discharging simulations in an indirect solar cooker. Discharging results of the TES system were presented using a constant flow-rate and variable flow-rate in order to maintain a desired power at a constant inlet temperature. The results of discharging the TES system at a constant flow-rate indicated a higher rate of heat utilization which was not found to be beneficial due to the cooking process as the maximum cooking temperature could not be maintained for the duration of the discharging period. On the other hand, the controlled load power discharging method had a slower initial rate of heat utilization but the maximum cooking temperature was maintained for most of the discharging process which is the desirable condition for the cooking process.

Kumar et al. [90] studied the truncated pyramid type solar box cooker (TPSBC) as shown in Fig. 14(a and b) and presented an exergy analysis based on the test protocol besides the schematic diagram of TPSBC with cooking vessels has been shown in Fig. 15. The variations in the exergy loss with respect to temperature difference was analysed for the selected temperature range from 60 °C to 95 °C. The peak exergy, quality factor, and the heat loss coefficient were found to be 7.124 W, 0.15 and 4.09 W/m^{2}K, respectively, for solar box type cooker. Kumar et al. [91] also studied the solar cookers of different geometries and presented an exergy based unified test protocol. In this study, four exergy based parameters viz. peak exergy, quality factor, exergy temperature difference gap product and heat loss coefficient were proposed for solar cookers at different topological designs. It was observed that these parameters resemble a parabolic curve for each design and the peak exergy can be accepted as a measure of devices fuel ratings. It was found that the exergy power lost is directly proportional to the temperature difference irrespective of the topology of the device and the slope of the straight line obtained through curve fitting.

Pandey et al. [92] evaluated the two different types of solar cookers viz. paraboloid type and box type using exergy analysis. The photographic view of the paraboloid and box type solar cookers has been shown in Fig. 16. In this study, the experiments were carried out with 1 and 2 L of water and 250 of rice. The exergetic efficiency with 1 and 2 L of water in paraboloid type cooker was found to be higher than that of the box type cooker, however, the efficiency with 2 L water was found to be higher than that of 1 L of water. The exergetic efficiency with 250 g of rice for

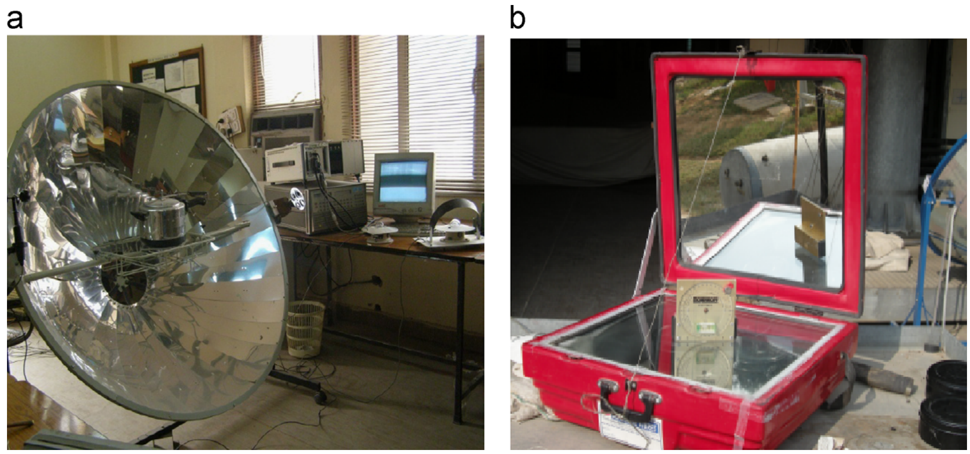


Fig. 16. Photographic view of Paraboloid and Box type solar cooker [92]. (a) Paraboloid solar cooker and (b) box type solar cooker.

paraboloid type solar cooker was found to be higher than that of the box type cooker. It was also found that the performance of the paraboloid type was better than that of the box type solar cooker. Cuce and Cuce [93] presented the comprehensive review on different types of solar cookers. They studied the performance evaluation, environmental aspects and feasibility study of different types of solar cookers such as panel type, box type and parabolic type. They suggested that for maximising the incident solar radiation Fresnel lenses or at least two booster mirrors should be used. For late night or evening cooking, use of phase change materials (PCMs) in solar cooker is recommended.

3. Solar photovoltaic systems

Smestad [94] examined concepts of hot carrier and light converter, indicating that electrons are ejected not only as heat but also as light. Carnot factor in solar cell theory was investigated by Landsberg and Markvart [95], they obtained an expression for the open-circuit voltage which is equal to the band gap multiplied by the Carnot efficiency. Thermodynamics and reciprocity of solar energy conversion was also discussed by Markvart and Landsberg [96] by taking into consideration the PV, photochemistry and photosynthesis. Sahin et al. [97] investigated the thermodynamic characteristics of the solar photovoltaic (PV) cells using exergy analysis. They developed and applied the new approach for the assessment of PV cells and found that the presented approach was realistic as it accounts for thermodynamic quantities such as enthalpy and entropy. They also analysed the PV cells on the basis of the energy and exergy efficiencies, the energy efficiency was found to be varying between 7% and 12% during the day while, the exergy efficiency was found to be varying between 2% and 8%.

3.1. Energy analysis

The actual output of the SPV module may be defined as below:

$$Q_o = V_{oc} I_{sc} FF \tag{39}$$

where V_{oc} is open circuit voltage, I_{sc} is short circuit current and FF is fill factor. The fill factor (FF) can be expressed as below:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{40}$$

Using the above definition, Eq. (40) can also be expressed as

$$Q_o = V_m I_m \tag{41}$$

Also the energy efficiency can be defined theoretically as below [98]:

$$\eta = \frac{V_{oc} \dot{I}_{sc}}{I_s A} \tag{42}$$

3.2. Exergy analysis

The input exergy i.e. exergy of solar radiation is given by [98]

$$\dot{Ex}_{solar} = \dot{Ex}_{in} = \left(1 - \frac{T_a}{T_s}\right) I_s A \tag{43}$$

where T_s is the temperature of sun which is taken as 5777 K. The exergy output of the SPV systems can be given as follows:

$$Ex_{out} = Ex_{elec} + Ex_{therm} + \dot{Ex}_d = \dot{Ex}_{elec} + I' \tag{44}$$

where $I' = \Sigma \dot{E}x = Ex_{d,elect} + Ex_{d,therm}$ which includes internal as well as external losses. Internal losses are electrical exergy destruction i.e. $Ex_{d,elect}$ and external losses are heat loss, $Ex_{d,therm}$ which is numerically equal to c for PV system.

$$\dot{Ex}_{elec} = E_{elec} - I' = V_{oc} I_{sc} - (V_{oc} I_{sc} - V_m I_m) \tag{45}$$

where, $V_{oc} I_{sc}$ represents the electrical energy and $(V_{oc} I_{sc} - V_m I_m)$ represents the electrical exergy destruction. Therefore from the above equation we find the electrical exergy as below:

$$\dot{Ex}_{elec} = V_m I_m \tag{46}$$

The thermal exergy of the system ($\dot{Ex}_{therm}$) which is defined as the heat loss from the photovoltaic surface to the ambient can be given as below:

$$\dot{Ex}_{therm} = \left(1 - \frac{T_a}{T_{cell}}\right) \dot{Q} \tag{47}$$

where $\dot{Q} = h_{ca} A (T_{cell} - T_a)$ and $h_{ca} = 5.7 + 3.8v$ are the heat transfer coefficients and v is the wind speed. Using the above equations the exergy output of SPV system can be written as below:

$$\dot{Ex}_{PV} = V_m I_m - \left(1 - \frac{T_a}{T_{cell}}\right) h_{ca} A (T_{cell} - T_a) \tag{48}$$

The power conversion efficiency (η_{pce}) of SPV can be defined as the ratio of the actual electrical output to the input energy ($I_s A$) on the SPV surface and given as below [98]:

$$\eta_{pce} = \frac{V_m I_m}{I_s A} \tag{49}$$

The power conversion efficiency can also be written in the terms of FF using the above equation as below [98]:

$$\eta_{pce} = \frac{FFV_{oc}I_{sc}}{I_s A} \tag{50}$$

The effect of temperature on efficiency of PV module can be obtained from the fundamental equations:

$$\eta_c = \eta_{T_{ref}}[\beta_{ref}(T_c - T_{ref}) + \gamma \log_{10} I_s] \tag{51}$$

where $\eta_{T_{ref}}$ is the module's electrical efficiency at the reference temperature, T_{ref}, and at solar radiation of 1000 W/m^2, β_{ref}, is the temperature coefficient and γ, is the solar radiation coefficient [99]. The temperature coefficient can be calculated from the below relation:

$$\beta_{ref} = \frac{1}{T_o - T_{ref}} \tag{52}$$

For variations in ambient temperature and irradiance the cell temperature can be estimated quite accurately with the linear approximation [100,101]

$$T_C = T_a + \left[\frac{T_{NOCT} - 20}{800\ W/m^2}\right] I_s \tag{53}$$

where, T_{NOCT} is the Nominal Operating Cell Temperature (NOCT). Therefore efficiency can be given by the below equation.

$$\eta_c = \eta_{ref}\left[1 - \beta_{ref}\left[T_a - T_{ref} + (T_{NOCT} - 20)x\frac{I_S}{I_{S_{NOCT}}}\right] + \gamma \log_{10} I_s\right] 100 \tag{54}$$

Usually $T_{ref} = 25\ ^\circ C$, average $\eta_{ref} = 12\%$ and average β_{ref}=0.0045 K. Therefore, the exergy efficiency (ψ) can be given as below [98]:

$$\psi = \frac{V_m I_m - (1 - (T_a/T_{cell}))h_{ca}A(T_{cell} - T_a)}{(1 - (T_a/T_s))I_s A} \tag{55}$$

However, the exergy efficiency can also be calculated using photonic energy as given by Joshi et al. [102]. The solar energy reaching on the earth surface can also be explained in terms of photonic energy from the sun which travels in the form of packets ($h\nu$) also termed as 'photons' [103]. The physical energy of a photon can be calculated as

$$E_{ph}(\lambda) = h\nu = \frac{hc}{\lambda} \tag{56}$$

The chemical potential/chemical exergy for the PV system can be given [98] as below:

$$\dot{E}_{chem} = E_{ph}(\lambda)\left(1 - \frac{T_{cell}}{T_s}\right) = \left(\frac{hc}{\lambda}\right)AN_{ph}\left(1 - \frac{T_{cell}}{T_s}\right) \tag{57}$$

where A is the surface area of PV module and N_{ph} is the number of photons on SPV module. Thus the chemical exergy is given by [104]

$$\dot{Ex}_{chem} = \eta_{pce}\dot{E}_{chem} \tag{58}$$

where η_{pce} is the power conversion efficiency.

3.3. Case studies

Bisquert et al. [105] studied on the physical and chemical principles of solar photovoltaic (SPV) conversion systems. The open-circuit voltage and chemical potential of a SPV cell was found to be dependent on the Carnot and statistical factors in their study. The performance characteristics of a photovoltaic (PV) and photovoltaic-thermal (PV/T) system was investigated by Joshi et al. [102] using energy and exergy analysis at a typical climatic zone in India. The energy efficiency was found in the range of 33–45%, while the corresponding exergy efficiency being in the range of 11–16%. However, for PV alone, the exergy efficiency was found to be varying in the range of 8–14% for a typical set of operating parameters. On the other hand, Hepbasli [106] carried out an extensive literature survey on exergy analysis of several solar energy systems especially the photovoltaic thermal systems and the expressions as given by Fujisawa and Tani [107] and Saitoh et al. [108] were found to be similar to those given by Hepbasli et al. [106]. Joshi et al. [109] carried out the thorough review on performance evaluation of photovoltaic (PV) and photovoltaic thermal (PV/T) systems based on energy and exergy approaches.

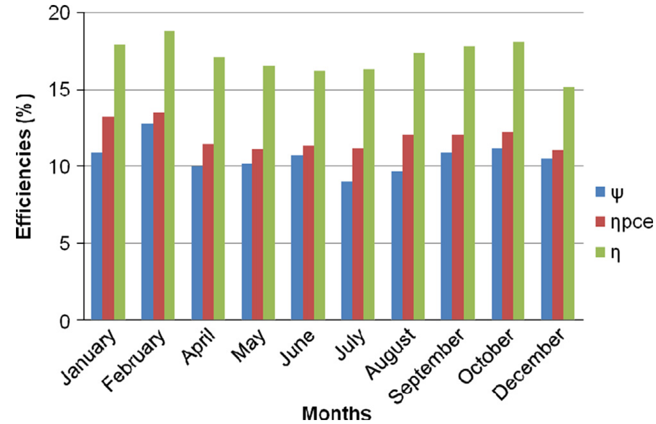


Fig. 17. Monthly variations of energy, power conversion and exergy efficiencies of multi-crystalline solar module [113].

Sarhaddi et al. [110] worked on performance analysis of solar photovoltaic thermal (PV/T) air collector using exergetic analysis. For the estimation of the electrical parameters of a PV/T air collector an improved electrical model was used in the present study and then in terms of design and climatic parameters a modified equation for the exergy efficiency of a PV/T air collector was derived. For a sample climatic, operating and design parameters, the thermal efficiency, electrical efficiency, overall energy efficiency and exergy efficiency of PV/T air collector were found to be 17.18%, 10.01%, 45% and 10.75% respectively. The literature survey on thermal modelling of photovoltaic (PV) modules and their applications was carried out by Tiwari et al. [111]. From the extensive literature survey, they found that the photovoltaic-thermal (PVT) modules were very promising devices and there exists a lot of scope to further improve the performances. The CIGS solar cells in the BIPVT system are the most suitable from the energy payback time (EPBT) and energy production factor (EPF) point of view. However, mono-crystalline solar cells in the building integrated photovoltaic thermal (BIPVT) system were found to be the most suitable from the life cycle conversion efficiency (LCCE) point of view.

Vats and Tiwari [112] carried out the performance study of a building integrated semitransparent photovoltaic thermal (BISPVT) system integrated on the roof of a room using energy and exergy analyses. In their study different types of SPV modules viz. monocrstallne Silicon (m-Si), polycrystalline Silicon (p-Si), amorphous silicon (a-Si), Cd-Te, CIGS and heterojunction with intrinsic thin layer (HIT) have been used for the comparative performance. They found that as the cell temperature increases the exergy efficiency decreases and the maximum annual electrical energy produced by HIT was found to be 810 kW h. However, the maximum annual thermal energy produced by a-Si was found to be 464 kW h and was also found to be suitable for space heating applications the efficiency of HIT and Si module was found to be 16.0% for HIT and 6.0% for the a-Si respectively. Pandey et al. [113] studied the annual performance of a multicrystalline based solar photovoltaic module using energy and exergy analyses for the

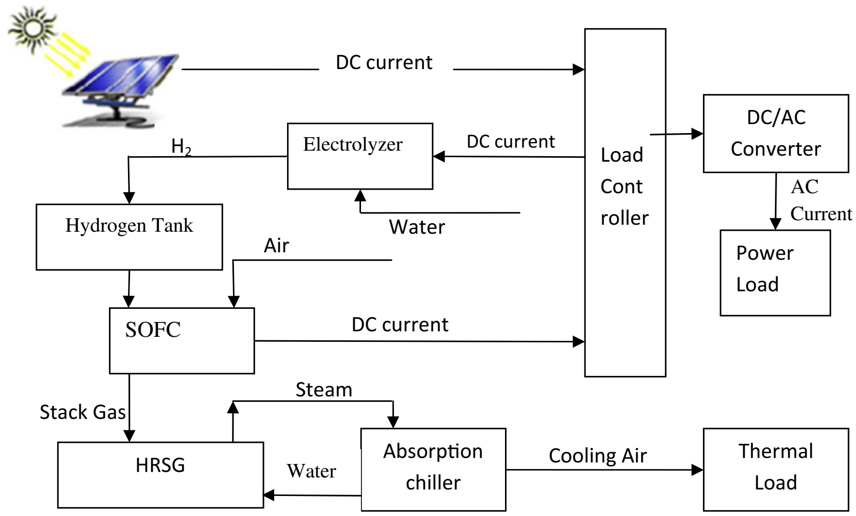


Fig. 18. Schematic of the photovoltaic-fuel cell CHP system for residential applications [114].

typical climatic zone in India. In the study different parameters such as, solar radiation, module temperature, open circuit voltage (V_{oc}), short circuit current (I_{sc}), voltage (V_m) and current (I_m) corresponding to maximum power point were collected with the help of weather monitoring system. They found that all the efficiencies i.e. energy, power conversion and exergy efficiencies are best for the month of February while a mix response was observed for the found to be for energy and power conversion efficiencies. The energy efficiency was found to be the least for the month of December, while, the exergy efficiency was found to be the least for the month of July, shown in Fig. 17. Hosseini et al. [114] worked on the energy and exergy analysis of hybrid solar-fuel cell combined heat and power system. The schematic diagram of the experimental set-up is shown in Fig. 18. The energy and exergy efficiency of the PV system were found 17% and 18.3%, respectively. However, the total (PV and Fuel cell combined) energy and exergy efficiencies were found to be 55.7% and 49% respectively.

4. Biomass cook stoves

Use of fire for cooking is as old as 100,000 years, however, initially open fire was used for roasting of meat [115]. As the time passes different advancements took place in the cooking technology from open-fire to shielded-fires. Three-stone fire arrangement was the most common form of shielded-fire while, as the development in the cookstove took place three stove fire transformed into the U-shape mud cookstove which is commonly known as traditional cookstove [116]. Due to lots of deficiencies in traditional cookstoves and oil crisis in 1970s, researchers around the globe started working on cookstove which led to the development of many improved cookstoves. Many of the improved cookstove programs (ICPs) were initiated to tackle the problem of deforestation, oil crisis and indoor air pollution (IAP). These programs were implemented by different countries with the help of various NGOs and other donor organizations yet they were not able to meet the objectives up-to the mark [117]. As far as India is concerned, development of biomass based cookstoves was started during the 1940s [118]. Focus of research during the 1980s and 1990s, was mainly on household energy issues in the developing countries due to deforestation and fuel scarcity [119]. However, in the beginning of 1990s focus of research shifted towards the health issues due to indoor air pollution [120].

Open burning of biomass fuels emits high levels of hazardous pollutants which include carbon monoxide (CO), nitrogen oxides (No_x), sulfur oxides (SO_x), suspended particulate matters (SPM) and a host of organic compounds [121]. The health impacts and the risk associated with indoor air pollution due to biomass fuel use were explained by Fullerton et al. [122]. They found that different types of diseases especially in female were found due to indoor air pollution, such as tuberculosis, respiratory infections including pneumonia and chronic obstructive pulmonary disease etc. Venkataraman et al. [123] stated that by using biomass fuels, lot of time and money was spent by poor people of the world which can be utilized for other useful purposes. The world health organization (WHO) has estimated that around 1.5 million people died every year and many other became victim of different diseases due to smoke from open fires and traditional cookstoves [124]. To short out the above mentioned problems numbers of efforts were made worldwide [125–129].

4.1. Energy analysis

Energy input is given by [130,98]

$$E_{in} = m_{wd}c_1 + x \times d \times c_2 \quad (59)$$

where m_{wd} is mass of wood, c_1 is calorific value of wood and c_2 is calorific value of kerosene, x is volume of kerosene, d is density of kerosene

Energy output is given by [130,98]

$$E_o = m_w C_p(T_{fw} - T_{iw}) + m_{pot} Cp_{Al}(T_{fp} - T_{ip}) \quad (60)$$

where C_p is specific heat of water, T_{fw} is final temperature of water, T_{iw} is initial temperature of water, Cp_{Al} is specific heat of aluminium , m_{pot} is mass of pot, T_{fp} is final temperature of pot, T_{ip} is initial temperature of pot.

Therefore, energy efficiency can be given as below:

$$\eta = \frac{Energy\ output}{Energy\ input} = \frac{E_o}{E_{in}} \quad (61)$$

4.2. Exergy analysis

An overall exergy balance can be written as

$$Exergy\ input - [Exergy\ recovered + Exergy\ loss] - Exergy\ consumption = Exergy\ accumulation \quad (62)$$



Fig. 19. Photographic view of various cookstove models studied experimentally [132]. (a) Envirofit model, (b) Harsha model, (c) Mangla model and (d) Vikram model.

Exergy input is given by [130,98]

$$Ex_{in} = m_{wd}c_1(1 - T_a/T_{fuel})\eta_c + xdc_2 \quad (63)$$

where T_a is ambient temperature, T_{fuel} is temperature of burning fuel. However, exergy input can also be by chemical exergy of solid industrial fossil fuel, which can be expressed as follows [86]:

$$\xi^0 = [(NCV)^0 + wh_{fg}]\phi_{dry} \quad (64)$$

where h_{fg} is enthalpy of evaporation of H_2O at standard temperature, for water substance at T=298.15 K, h_{fg}=2442 kJ/kg, N_{ph} is mass fraction of moisture in fuel, NCV^0 is net calorific value of moist fuel. For dry organic substances contained in solid fossil fuel consisting of C, H, N, O with mass ratio to carbon 2.67 > o/c > 0.667, which in particular includes wood.

$$\phi_{dry} = \frac{1.0438 + 0.1882(h/c) - 0.2509(1 + 0.7256(h/c)) + 0.0383(n/c)}{1 - 0.3035(o/c)} \quad (65)$$

where c, h, n and o are the mass fractions of C, H, N and O respectively. The exergy output is given by [130]

$$Ex_o = m_wC_p(T_{fw} - T_{iw})(1 - T_a/T_{fw}) + m_{pot}Cp_{Al}(T_{fp} - T_{ip})(1 - T_a/T_{fp}) \quad (66)$$

The exergy efficiency can be given by

$$\psi = \frac{m_wC_p(T_{fw} - T_{iw})(1 - T_a/T_{fw}) + m_{pot}Cp_{Al}(T_{fp} - T_{ip})(1 - T_a/T_{fp})}{m_{wd}c_1(1 - T_a/T_{fuel}) \times \eta_c + x \times d \times c_2} \quad (67)$$

4.3. Case studies

A study by Zhong et al. [131] revealed that biomass is converted to a liquid fuel with an approximately high energy, which is called bio-crude. The maximum exergy efficiency of this process can be as high as 86% and was calculated based on the equations developed by Szargut et al. [132]. An energy analysis of rape seed oil methyl ester (RME) was investigated by Kalinc et al. [133] and it was found that the process analysis method is a common method to obtain reasonable data for energy and exergy analysis. The chemical exergy of liquid fuels was calculated and estimated and the chemical exergy of rape seed oil and RME was reported to be 44.5 MJ/kg and 50.5 MJ/kg respectively. Ojeda et al. [134] evaluated the lingo-cellulosic biomass and calculated the exergy of main stream process such as re-treatment, fermentation and separation. Saidur et al. [135] carried out the literature survey on the exergy analysis of various biomass viz. herbaceous and agricultural biomass, woody biomass, contaminated biomass and industrial biomass, aquatic biomass. They found that the gasification, methanation and CO_2 removal were the main sources of exergy losses.

Tyagi et al. [130] carried out the energy and exergy analysis of four different types of cookstove models viz. Envirofit, Mangla, Harsha and Vikram. The photographic view of various cook stove models used in the study is given in Fig. 19. For experimental study water boiling test has been carried out by following the testing procedure of the Bureau of Indian Standards (BIS). The energy and exergy efficiencies were evaluated and plotted against the heating time for each cook-stove model. From the analysis it was found that both the efficiencies of Envirofit model were higher than that of rest of the three models. The variation in energy and exergy

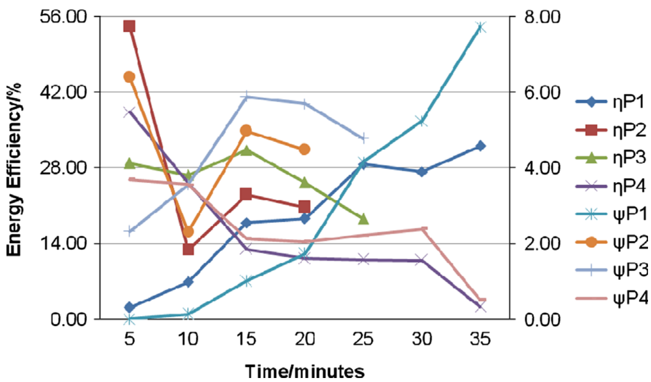


Fig. 20. Energy and exergy efficiencies versus time of a typical cookstove model [132].

efficiencies against the heating time for Envirofit model for different pots used in the study was shown in Fig. 20. Finally it was found that the energy efficiency for all the cases was much higher than that of exergy efficiency, which can be explained in terms of the quality of energy gained by the hot water during the testing procedure.

5. Conclusions

A comprehensive literature review on energy and exergy analyses of renewable energy conversion systems including solar air heater, solar water heater, solar photovoltaic and cooking devices such as solar cooker and biomass cook stoves have been carried out. From the literature review of exergy analysis of different renewable energy conversion systems, it was found that

- exergy analysis of the solar thermal devices in general and solar air/water heaters in particular, exergy analysis of photovoltaics, exergy analysis of biomass based energy systems is scant.
- Both the efficiencies i.e. energy and exergy for solar air heater were found to be better with thermal energy storage than those without thermal energy storage.
- In general, energy efficiency for all the renewable energy systems has been found to be always greater than that of exergy efficiency.
- Exergetic efficiency for solar water heaters were found to be very low in the range of 3–5% as investigated by different authors.
- Performance of paraboloid type solar has been found to be better than that of box type solar cooker.
- It is also recommended to use photovoltaic thermal (PV/T) collectors than photovoltaic (PV) alone for better performance and economic benefits of these systems.

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